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Diffusion of hidden charm mesons in hadronic medium

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Abstract

The drag and diffusion coefficients of a hot hadronic medium have been evaluated by using hidden charm mesons as probes. The scattering amplitudes required for the evaluation of these coefficients are calculated using an effective theory and scattering lengths obtained from lattice QCD calculations. It is found that although the magnitude of the transport coefficients are small their temperature variation is strong. The insignificant momentum diffusion of J/ψ in the hadronic medium keeps their momentum distribution largely unaltered. Therefore, the task of characterization of quark gluon plasma by using the observed suppression of J/ψ at high momentum will be comparatively easier.

Keywords: Drag and diffusion coefficients; Hidden charm meson; Heavy ion collision

1. Introduction

The experimental evidence of J/ψ suppression by NA50 [1], NA60 [2] as well as by the PHENIX [3] Collaboration has long been suggested as a signal of quark–gluon plasma (QGP) formation in heavy ion collisions [4]. However, other mechanisms such as the J/ψ absorp-

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tion by comoving hadrons have also been proposed as an alternative mechanism to explain the suppression [5], indicating that the inelastic scattering rates of J/ψ in the hadronic phase is significant [6–8]. In addition, the opening of $J/\psi \to D\overline{D}$ decay in the medium due to in-medium modification of D mesons [9,10] may also play a significant role in J/ψ suppression in a hadronic environment.

Heavy quark transport in hadronic matter is a topic of high contemporary interest [11–17]. The drag and diffusion of open charm [13] and bottom [15] mesons and the role of hadronic matter in their suppression in heavy ion collisions [18] have been investigated using effective hadronic interactions based on heavy quark effective theory. The suppression of heavy flavors in the hadronic phase in comparison to QGP was found to be smaller at LHC than at RHIC, suggesting that the characterization of QGP at LHC would be less complicated than at RHIC [18].

Recently we have obtained the drag and diffusion of the Λ_c baryon in hadronic matter [19] and found those to be significant. In fact, the drag of the Λ_c being lower than that of the D mesons was seen to non-trivially affect the p_T dependence of the Λ_c/D ratio and thus the R_{AA} of single electrons originating from the decay of Λ_c. Motivated by these results we proceed to study the temperature variation of the drag and diffusion coefficients of J/ψ and η_c in a comoving hadronic medium. For evaluating these quantities the required interaction cross sections have been evaluated employing an effective hadronic Lagrangian. Drag and diffusion coefficients have also been estimated using T-matrix elements extracted from scattering lengths obtained from lattice QCD calculations.

In the next section we provide the formulae for the drag and diffusion coefficients followed by a discussion on the matrix elements of elastic scattering of the J/ψ with the light vector mesons in section 3. Results are given in Section 4 and finally a summary in Section 5. We provide the squared matrix elements in the appendix.

2. Formalism

The drag (γ) and diffusion (D) coefficients of J/ψ and η_c are obtained from the elastic scattering of J/ψ with the light thermal hadrons (H) which constitute the equilibrated thermal medium. For the process $J/\psi, \eta_c(p_1) + H(p_2) \to J/\psi, \eta_c(p_3) + H(p_4)$, the drag γ can be expressed as [20]:

$$\gamma = p_i A_i / p^2 \,, \tag{1}$$

where A_i is given by

$$\begin{aligned} A_i = &\frac{1}{2E_{p_1}} \int \frac{d^3p_2}{(2\pi)^3 E_{p_2}} \int \frac{d^3p_3}{(2\pi)^3 E_{p_3}} \int \frac{d^3p_4}{(2\pi)^3 E_{p_4}} \frac{1}{g_{(J/\psi,\eta_c)}} \\ &\sum \overline{|M|^2} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) f(p_2)\{1 \pm f(p_4)\}[(p_1 - p_3)_i] \\ \equiv &\langle\langle (p_1 - p_3) \rangle\rangle \,. \end{aligned} \tag{2}$$

The $g_{(J/\psi,\eta_c)}$ is the statistical degeneracy of the probes, J/ψ or η_c. The thermal distribution function $f(p_2)$ of the hadron H in the incident channel takes the form of Bose–Einstein or Fermi–Dirac distribution depending on its spin and $1 \pm f(p_4)$ are their corresponding Bose enhanced or Pauli blocked phase space factor in their final states. The drag coefficient of Eq. (2) is just a measure of the thermal average of the momentum transfer, $p_1 - p_3$ weighted by the square of the invariant amplitude $\overline{|M|^2}$ for the elastic scattering of J/ψ and η_c with thermal hadrons, generically denoted as H.

In a similar way, the diffusion coefficient D can be defined as:

$$D = \frac{1}{4}\left[\langle\langle p_3^2\rangle\rangle - \frac{\langle\langle (p_1 \cdot p_3)^2\rangle\rangle}{p_1^2}\right] . \tag{3}$$

With an appropriate choice of $T(p_3)$ both the γ and D can be obtained from a single expression, which is given by

$$\ll T(p_1) \gg = \frac{1}{512\pi^4}\frac{1}{E_{p_1}}\int_0^\infty \frac{p_2^2 dp_2 d(\cos\chi)}{E_{p_2}}\hat{f}(p_2)\{1 \pm f(p_4)\}\frac{\lambda^{\frac{1}{2}}(s, m_{p_1}^2, m_{p_2}^2)}{\sqrt{s}}$$
$$\int_1^{-1} d(\cos\theta_{c.m.})\frac{1}{g}\sum\overline{|M|^2}\int_0^{2\pi} d\phi_{c.m.} T(p_3) , \tag{4}$$

where $\lambda(s, m_{p_1}^2, m_{p_2}^2) = (s - m_{p_1}^2 - m_{p_2}^2)^2 - 4m_{p_1}^2 m_{p_2}^2$, is the triangular function.

3. Dynamics

In this section we will discuss the two body elastic scattering of J/ψ with the constituent hadrons in the medium within the framework of SU(4) symmetry. Some of the relevant features of these interactions are mentioned below and for details we refer to [6,7] to avoid repetition. The aim of the present work is to estimate the momentum diffusion coefficient of hot hadrons produced as a result of phase transitions from an expanding QGP formed in heavy ion collisions at relativistic energies. That is we would like to understand how efficiently the momentum of the J/ψ propagating through a hadronic medium is transferred to the medium enabling to estimate momentum diffusion or shear viscous coefficient of the medium [21]. Since J/ψ is used here as a probe to extract the coefficient of momentum diffusion for characterizing the medium, its detection in the final reaction channel is essential. Therefore, the inelastic processes which kill the J/ψ are not considered here. For this reason, we consider only the two body elastic processes *e.g.* $h_1 + J/\psi \to h_1 + J/\psi$, in the present work ($h_i$'s are hadrons in the medium). Although, J/ψ appears in the final channel in the processes like $h_1 + J/\psi \to h_2 + h_3 + J/\psi$, analogous to the gluon bremsstrahlung by heavy quarks in the QGP phase, are also ignored, as their contributions may be smaller than the two body elastic processes.

The hot hadronic matter produced in the later stages of relativistic heavy ion collisions is populated by light pseudo-scalars and vector mesons like π, K, η, ρ^0, ω and ϕ. The magnitude of hadronic scatterings are estimated either by introducing different perturbative or non-perturbative approach at quark level [22,23] or by using an effective Lagrangian to calculate Feynman diagrams. Concerning the latter approach, the SU(4) is the smallest possible symmetry group which includes the charmonium state explicitly along with the light and heavy pseudo-scalar and vector mesons. The corresponding pseudo-scalar and vector meson matrices as well as the chiral Lagrangian are given in Refs. [6,7] which can be readily used for the present purpose of evaluating the drag and diffusion coefficients of J/ψ in hadronic matter. Since SU(4) symmetry is badly broken by the large mass of the charmed meson, terms involving hadron masses are included in the chiral Lagrangian using the experimentally determined values of SU(4) model parameters.

Since pions are identified with the Nambu–Goldstone bosons of QCD their interaction strength with other hadrons should abruptly decrease in the chiral limit. We recall the standard relation [24,25] for the s-wave scattering length of pion with a heavy meson like J/ψ,

$$a_{l=0}^{\pi J/\psi} = -(1+\frac{m_\pi}{m_{J/\psi}})^{-1}\frac{m_\pi}{4\pi F_\pi^2}\vec{I}_\pi \cdot \vec{I}_{J/\psi} + \mathcal{O}(m_\pi^2), \tag{5}$$

with the dot product defined as,

$$\vec{I}_\pi \cdot \vec{I}_{J/\psi} = \frac{1}{2}[I(I+1) - I_{J/\psi}(I_{J/\psi}+1) - I_\pi(I_\pi+1)]. \tag{6}$$

I_π, $I_{J/\psi}$ are respectively the isospin quantum numbers of the pion and J/ψ and I represents their total isospin quantum number. In the chiral limit ($m_\pi \to 0$), the first term of eq. (5) exactly vanishes. When the other hadron is J/ψ or η_c, this term in (5) vanishes exactly, not only in the chiral limit but also for finite pion mass (because $\vec{I}_\pi \cdot \vec{I}_{J/\psi} = 0$). Hence the contribution of the pion in the charmonium scattering length starts from $\mathcal{O}(m_\pi^2)$, which indicates that at least at low energy the pion–charmonium interaction is weak. This is in confirmation with the results obtained using the meson exchange model of Haglin et al. [6], where it was found that the elastic channels of J/ψ interaction involving the light pseudo-scalars are significantly smaller in comparison with the vector mesons. They have found that π, η, and K elastic cross sections with J/ψ are of order 100 fb, 1 nb and 100 nb respectively. On the other hand the contributions for elastic scattering with ρ^0, ω and ϕ mesons are quantitatively much larger, up to about a few mb. Hence, the elastic scattering of the heavy charmonium states like J/ψ and η_c with vector mesons are considered here. These processes involve vector–vector–pseudo-scalar interactions which are not present in the chiral Lagrangian. The relevant effective interaction describing $J/\psi + V \to \eta_c \to J/\psi + V$ processes [6] is

$$\mathcal{L}_{JV\eta_c} = g_{JV\eta_c}\epsilon_{\alpha\beta\sigma\delta}\{\partial^\alpha J/\psi^\beta\}\{\partial^\sigma V^\delta\}\eta_c\ , \tag{7}$$

where $g_{JV\eta_c} = 2.44\ \text{GeV}^{-1}$, $7.03\ \text{GeV}^{-1}$ and $4.51\ \text{GeV}^{-1}$ for $V = \rho^0, \omega$ and ϕ respectively [6].

The s and u channel diagrams for the process $J/\psi + V \to \eta_c \to J/\psi + V$ are shown in the panels (A) and (B) of Fig. 1. The matrix elements for the two channels are respectively given by,

$$M_s = -g_{JV\eta_c}^2[\varepsilon^\beta(p_1)\varepsilon^\delta(p_2)\varepsilon^{*\beta_1}(p_3)\varepsilon^{*\delta_1}(p_4)\epsilon_{\alpha\beta\sigma\delta}\ p_1^\alpha p_2^\sigma\ \epsilon_{\alpha_1\beta_1\sigma_1\delta_1}\ p_3^{\alpha_1}p_4^{\sigma_1}]/(s-m_{\eta_c}^2) \tag{8}$$

and

$$M_u = -g_{JV\eta_c}^2[\varepsilon^\beta(p_1)\varepsilon^{*\delta}(p_4)\varepsilon^{\delta_1}(p_2)\varepsilon^{*\beta_1}(p_3)\epsilon_{\alpha\beta\sigma\delta}\ p_1^\alpha p_4^\sigma\ \epsilon_{\alpha_1\beta_1\sigma_1\delta_1}\ p_2^{\sigma_1}p_3^{\alpha_1}]/(u-m_{\eta_c}^2). \tag{9}$$

The s and u channel diagrams of the η_c meson scattering with the thermalized vector mesons by exchanging J/ψ are shown in the panels (C) and (D) of Fig. 1. The respective matrix elements are given by

$$\begin{aligned}M_s = &-g_{JV\eta_c}^2[\varepsilon^\delta(p_2)\varepsilon^{*\delta_1}(p_4)\epsilon_{\alpha\beta\sigma\delta}(p_1+p_2)^\alpha p_2^\sigma \epsilon_{\alpha_1\beta_1\sigma_1\delta_1}(p_1+p_2)^{\alpha_1}p_4^{\sigma_1}]\\ &\{-g^{\beta\beta_1} + \frac{(p_1+p_2)^\beta(p_1+p_2)^{\beta_1}}{m_J^2}\}/(s-m_J^2)\end{aligned} \tag{10}$$

and

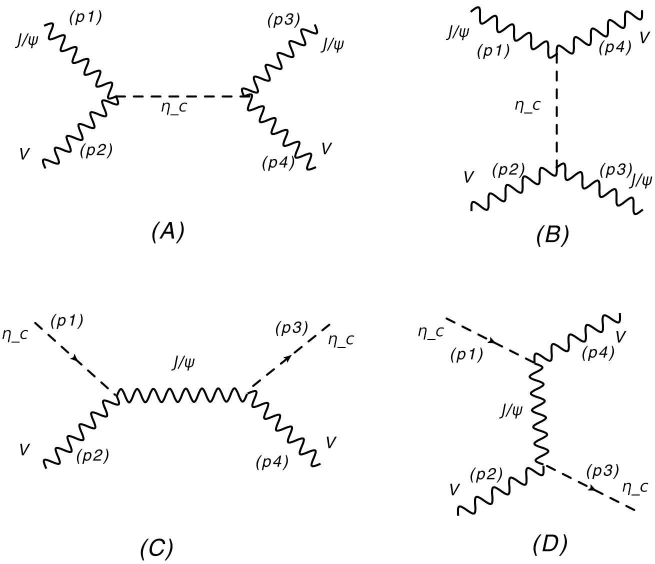

Fig. 1. The s and u channel of J/ψ–V scattering via η_c exchange are respectively depicted in diagrams (A) and (B). Diagrams (C) and (D) are the same for the η_c–V scattering via intermediary J/ψ.

$$M_u = -g^2_{JV\eta_c}[\varepsilon^{*\delta}(p_4)\varepsilon^{\delta_1}(p_2)\epsilon_{\alpha\beta\sigma\delta}(p_1-p_4)^{\alpha}p_4^{\sigma}\epsilon_{\alpha_1\beta_1\sigma_1\delta_1}(p_1-p_4)^{\alpha_1}p_2^{\sigma_1}]$$
$$\{-g^{\beta\beta_1}+\frac{(p_1-p_4)^{\beta}(p_1-p_4)^{\beta_1}}{m_J^2}\}/(u-m_J^2)\ . \quad (11)$$

The spin averaged modulus square of the total amplitudes corresponding to the amplitudes given above are listed in the Appendix. With the help of these amplitudes we finally obtain the interaction cross section as a function of the centre of mass energy ($\sqrt{s}$). The elastic scattering cross sections of J/ψ with vector mesons ρ^0, ω and ϕ are plotted against $\sqrt{s}$ in Fig. 2. We find that the cross sections obtained due to the interaction of J/ψ with ρ^0 and ω have values within 1 to 10 mb for $\sqrt{s}\sim 8$ GeV. This is in good agreement with the results provided in Ref. [6].

Finally using these amplitudes of the elastic scattering between the charmonia (J/ψ and η_c) with the vector mesons and putting them in Eq. (4) we obtain the drag and diffusion coefficients of the J/ψ and η_c in hadronic matter.

The scattering lengths of charmonia (J/ψ and η_c) with light hadrons (π, ρ^0 and N) have been studied in the literature in order to estimate the interactions of J/ψ and η_c with light hadrons at low energy. In [25] the low-energy interactions of J/ψ as well as η_c with π, ρ^0 or N have been investigated by Yokokawa et al. in the quenched lattice QCD framework. From the scattering lengths, a (say) of J/ψ or η_c interacting with light hadrons H (where $H=\pi$, ρ^0 and N) we can extract the dimensionless threshold, the T-matrix element by using the relation

$$T = 4\pi[m_{(J/\psi,\eta_c)} + m_H]a\ . \quad (12)$$

Using these $\overline{|T|^2}$ in place of $\overline{|M|^2}$ in Eq. (4), we can get an alternative estimation of the diffusion and drag coefficients of J/ψ as well as η_c mesons in hadronic matter [15]. The extracted values of T-matrices from a (in fm) are given in Table 1.

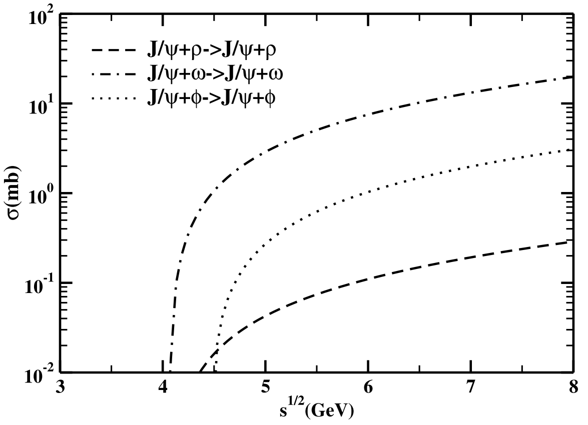

Fig. 2. Scattering cross section of J/ψ with vector mesons ρ^0, ω and ϕ using effective interaction (7).

Table 1
Table showing the extracted values of T-matrix from the spin averaged values of scattering length, a, which are obtained in the framework of quenched lattice calculation by Yokokawa et al. [25].

	$J/\psi\pi$	$J/\psi\rho^0$	$J/\psi N$
a (fm)	0.0119 ± 0.0039	0.23 ± 0.08	0.71 ± 0.48
T	2.45 ± 0.8	56.69 ± 19.71	182.60 ± 123.45
	$\eta_c\pi$	$\eta_c\rho^0$	$\eta_c N$
a (fm)	0.0113 ± 0.0035	0.21 ± 0.11	0.70 ± 0.66
T	2.24 ± 0.69	50.20 ± 26.29	174.85 ± 164.86

4. Results

We begin this section by plotting in Fig. 3 the drag coefficients of the J/ψ (solid line) and η_c (dashed line) as a function of temperature. As mentioned before, the drag is a measure of the momentum transfer between the J/ψ (or η_c) and the thermal hadrons weighted by the interactions implemented through $|M|^2$. The average momentum of the bath particles increases with temperature. Therefore, the thermal hadrons gain the ability to transfer larger momentum through interactions as the temperature of the bath increases. This causes the rise of drag at high temperatures both for J/ψ and η_c.

In Fig. 4 we show the corresponding results for the case where the amplitudes are extracted from scattering lengths. In this case the difference in drag coefficients between the J/ψ and η_c turns out to be insignificant. This is because the scattering lengths obtained from lattice are of similar magnitude unlike the effective interaction which is different for the J/ψ and η_c.

The drag coefficient estimated by taking the scattering length from Ref. [25] differs conspicuously from its value obtained in effective Lagrangian approach. This is anticipated because the calculations performed in the two approaches involve very different values of dynamical quantities *i.e.*, the scattering cross section. A straightforward comparison of the magnitude of the cross sections will help in understanding the difference in the value of the drag coefficient. The magnitude of the $J/\psi - \rho$ elastic cross section as displayed in Fig. 2 is $\sim$ a few tenth of a mb which is smaller than the value obtained in [25] (where the pseudoscalars are far from their physical

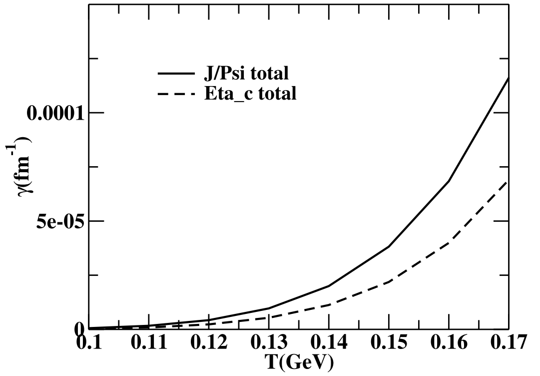

Fig. 3. The drag coefficient (γ) as a function of temperature calculated in the effective Lagrangian approach.

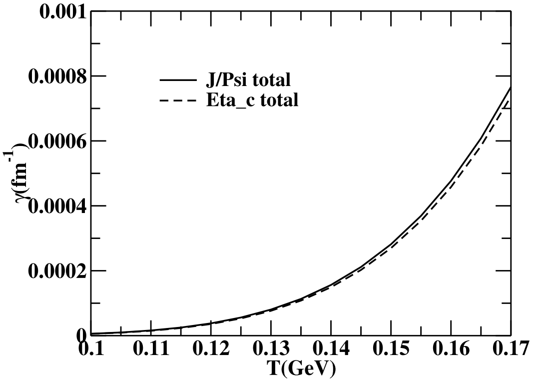

Fig. 4. The drag coefficient (γ) as a function of temperature obtained using scattering lengths.

masses and coupling strength is presumably larger). This indicates that drag estimated within the effective Lagrangian model will be smaller than scattering length approach as exhibited in Figs. 3 and 4. However, it is crucial to note that with either value of the drag coefficient the momentum distribution of the J/ψ in the hadronic medium remain largely unaltered.

Now we display our results for the diffusion coefficient, D which is plotted against T in Figs. 5 and 6 for the effective Lagrangian and scattering length approaches respectively. In addition to the results of direct calculation using eq. (4), the results from the fluctuation-dissipation theorem (FDT) are also shown by solid (J/ψ) and dashed (η_c) lines with solid circles in Figs. 5 and 6. As for the earlier case of the drag coefficient, the diffusion in the scattering length approach is similar for the J/ψ and η_c mesons. The rise of diffusion coefficients with increasing temperature has the same origin as that of drag coefficients as explained above.

The heavy quarks (HQs) momentum suppression have been used to understand the properties of the QGP matter. Several perturbative QCD (pQCD) based analyses (see [26–28] and refs. therein) have been performed to study the suppression of HQs at high momentum region, where the pQCD techniques are reliable. For an accurate characterization of the QGP it is essential to discern the role of hadronic matter at the same kinematic domain. In this spirit the suppression of heavy mesons (open or hidden) may also be considered at the high momentum domain to estimate and disentangle the contributions from the hadronic matter.

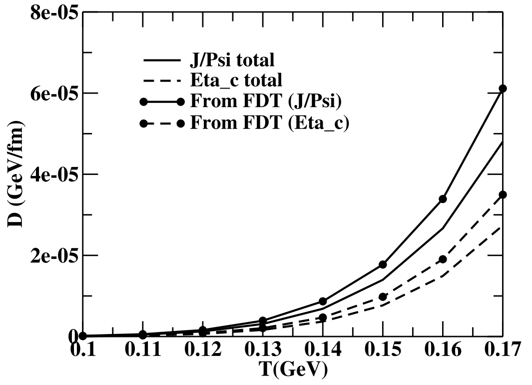

Fig. 5. The diffusion coefficient (D) as a function of temperature calculated in the effective Lagrangian approach.

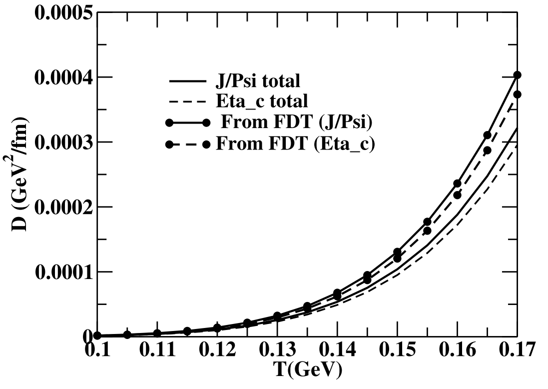

Fig. 6. The diffusion coefficient (D) as a function of temperature obtained using scattering lengths.

The suppression of J/ψ (or η_c) at high momenta in nuclear collisions compared to proton–proton collision may be approximately estimated as, $R_{AA} \sim e^{-\Delta\tau\,\gamma}$ [12], where $\Delta\tau$ is typically the life time of the hadronic phase. Taking $\Delta\tau \sim 5$ fm/c and $\gamma \sim 10^{-4}$ one finds that R_{AA} is close to unity. Thus the hadronic phase does not play a significant role in the suppression of J/ψ (or η_c) at high p_T, therefore, a significant suppression, if observed experimentally, is likely to originate from the QGP phase of the evolving fireball produced in relativistic heavy ion collisions. In the earlier investigations [14,12,15] on D meson diffusion in hadronic matter, our estimations [15] from scattering lengths of D meson with other hadrons are more or less close to the estimations of other group [14,12] [$\gamma(\text{fm}^{-1}) \approx 0.012$–$0.032$ [14], 0.01–0.03 [12], 0.005–0.027 [15] within hadronic temperature domain $T = 120$–170 MeV]. On this basis, our estimations for J/ψ are expected to be similar with other models.

5. Summary and discussions

We have estimated the drag and diffusion coefficients of J/ψ and η_c in a hot hadronic medium using effective field theory and T matrices obtained within the ambit of quenched lattice QCD calculations. The values of these transport coefficients turn out to be small compared to the values obtained for open charmed hadrons for the temperature range relevant for the hadronic phase expected to be formed in the later stages of the evolving matter produced in nuclear collisions at RHIC and LHC energies. We find that the suppression of J/ψ and η_c at high momentum may not be significant in the hadronic phase. This finding prevails with the values of the drag and diffusion coefficients obtained with inputs either from lattice QCD or effective Lagrangian approach *i.e.* the main conclusion of this work is not affected by the variation in the values of drag obtained within the ambit of the two approaches adopted here.

Therefore, such a suppression if observed experimentally will possibly indicate the creation of QGP in heavy ion collisions at relativistic energies.

Of late the shear viscosity (η) to entropy density (s) ratio (η/s) has been considered as a useful quantity to characterize the matter formed in heavy ion collisions at RHIC and LHC energies. The value of this ratio is found to be small from the analysis of experimental data [29], which led to the conclusion that the matter formed in these collision behaves like a perfect liquid.

In the present work we find that the momentum diffusion of J/ψ is small *i.e.* the transfer of momentum between J/ψ and hadrons is inefficient which means that the shear viscosity is large [21]. This again indicates that the role of hadrons in the suppression of J/ψ in the high momentum domain is inconsequential compared to QGP.

It may be mentioned that the role of the nucleons has been neglected in evaluating the drag and diffusion coefficients of J/ψ and η_c within the ambit of effective Lagrangian approach here. However, the inclusion of the nucleons will not change the conclusion because we found that an enhancement of the drag coefficient, γ by a factor of 4 will suppress the p_T spectra by a factor less than 1%.

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Appendix A

The modulus square of the spin averaged total amplitude for the processes of $J/\psi + V \to \eta_c \to J/\psi + V$ is given by the following expression,

$$\overline{|M|^2} = \overline{|M_s|^2} + \overline{|M_u|^2} + 2\overline{M_s M_u^*} \tag{13}$$

where the respective terms in the expression are given by

$$\overline{|M_s|^2} = \frac{g^4_{JV\eta_c}}{36(s - m^2_{\eta_c})^2}\lambda^2(s, m^2_{J/\psi}, m^2_V)$$

$$\overline{|M_u|^2} = \frac{g^4_{JV\eta_c}}{36(u - m^2_{\eta_c})^2}\lambda^2(u, m^2_{J/\psi}, m^2_V)$$

$$\overline{M_s M_u^*} = \frac{g^4_{JV\eta_c}}{9(s - m^2_{\eta_c})(u - m^2_{\eta_c})} I\ ,$$

where,

$$I=\frac{1}{8}[m_J^8+s^4+2s^3(t-2m_V^2)+2sm_V^4(t-2m_V^2)-4m_J^6(s+m_V^2)+m_V^4(t^2+m_V^4)$$
$$+s^2(t^2-4tm_V^2+6m_V^4)+m_J^4\{6s^2+t^2+6m_V^4+2s(t+2m_V^2)\}$$
$$-2m_J^2\{2s^3+2s(t-m_V^2)(s+m_V^2)+m_V^2(t^2+2m_V^4)\}],$$

and $\lambda(x,y,z)=x^2+y^2+z^2-2xy-2yz-2zx$ is the triangular function. Next, the spin averaged modulus square of total amplitude for the processes $\eta_c+V\to J/\psi\to\eta_c+V$ are given by

$$\overline{|M|^2}=\overline{|M_s|^2}+\overline{|M_u|^2}+2\overline{M_sM_u^*} \tag{14}$$

where

$$\overline{|M_s|^2}=(g^4_{JV\eta_c}/3)\left\{\frac{s}{4}(t-4m_V^2)(s+m_V^2-m_{\eta_c}^2)^2+\frac{1}{8}(s+m_V^2-m_{\eta_c}^2)^4\right.$$
$$\left.+\frac{s^2}{4}(t^2-4tm_V^2+8m_V^4)\right\}/(s-m_J^2)^2\ , \tag{15}$$

$$\overline{|M_u|^2}=(g^4_{JV\eta_c}/3)\left\{\frac{u}{4}(t-4m_V^2)(u+m_V^2-m_{\eta_c}^2)^2+\frac{1}{8}(u+m_V^2-m_{\eta_c}^2)^4\right.$$
$$\left.+\frac{u^2}{4}(t^2-4tm_V^2+8m_V^4)\right\}/(u-m_J^2)^2, \tag{16}$$

and

$$\overline{M_sM_u^*}=(g^4_{JV\eta_c}/3)\Big[m_{\eta_c}^8+m_V^8+s^4-4m_{\eta_c}^6(m_V^2+s)+2m_V^4s(3s-t)$$
$$+2s^3t-st^3+m_V^6(-4s+2t)-2m_V^2s(2s^2+st-2t^2)$$
$$+2m_{\eta_c}^4\{3m_V^4+m_V^2(2s+t)+s(3s+t)\}-2m_{\eta_c}^2\{2m_V^6-2m_V^2s(s-2t)$$
$$-2m_V^4(s-t)+s(2s^2+2st-t^2)\}\Big]/8(s-m_J^2)(u-m_J^2). \tag{17}$$

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